Methane Pyrolysis Techno-Economic Modelling with H2FAST

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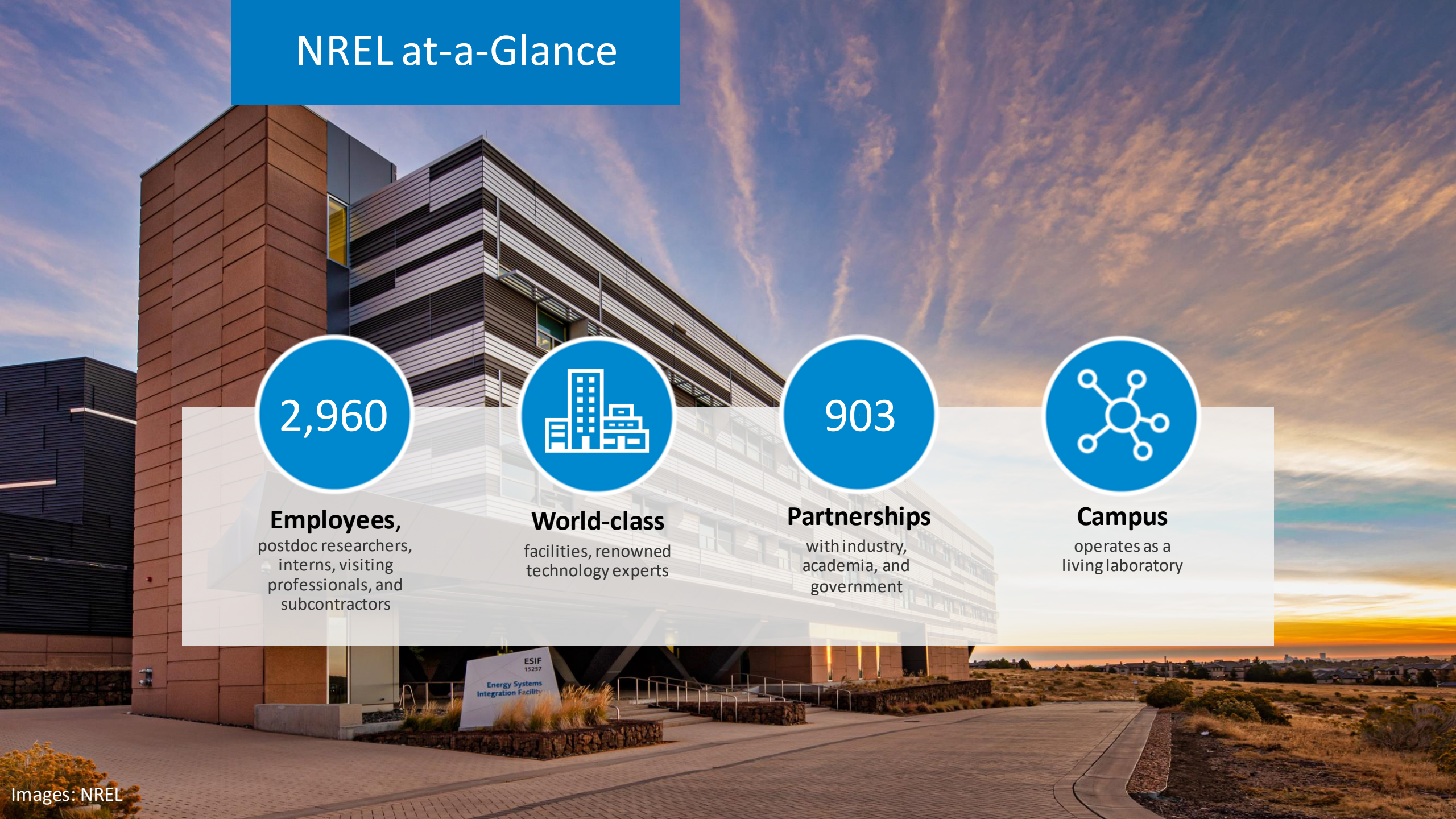
January 12, 2022

NREL at-a-Glance



2,960

Employees,
postdoc researchers, interns, visiting professionals, and subcontractors

World-class
facilities, renowned technology experts

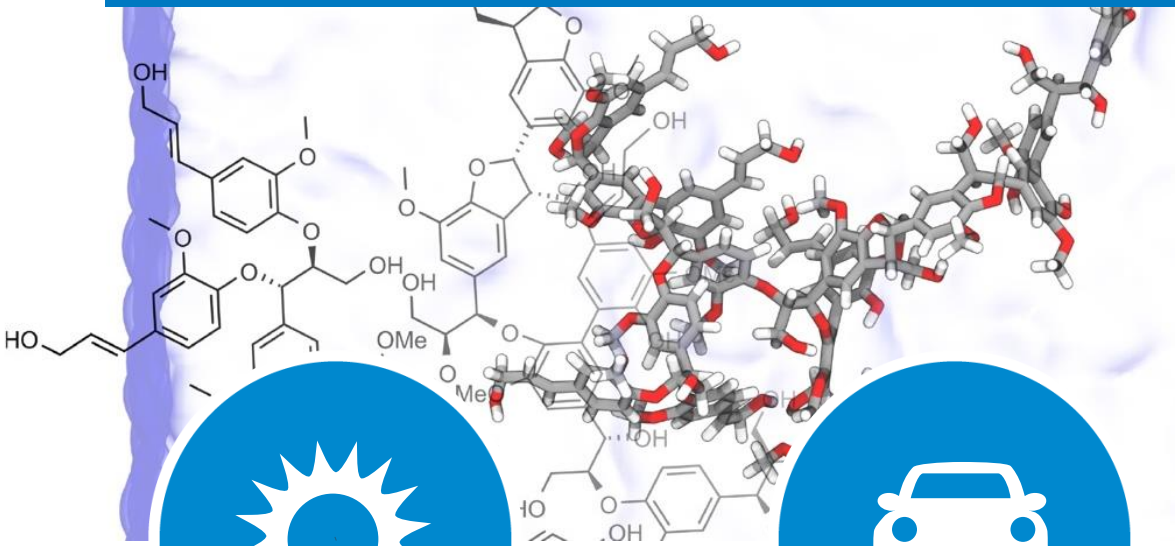
903

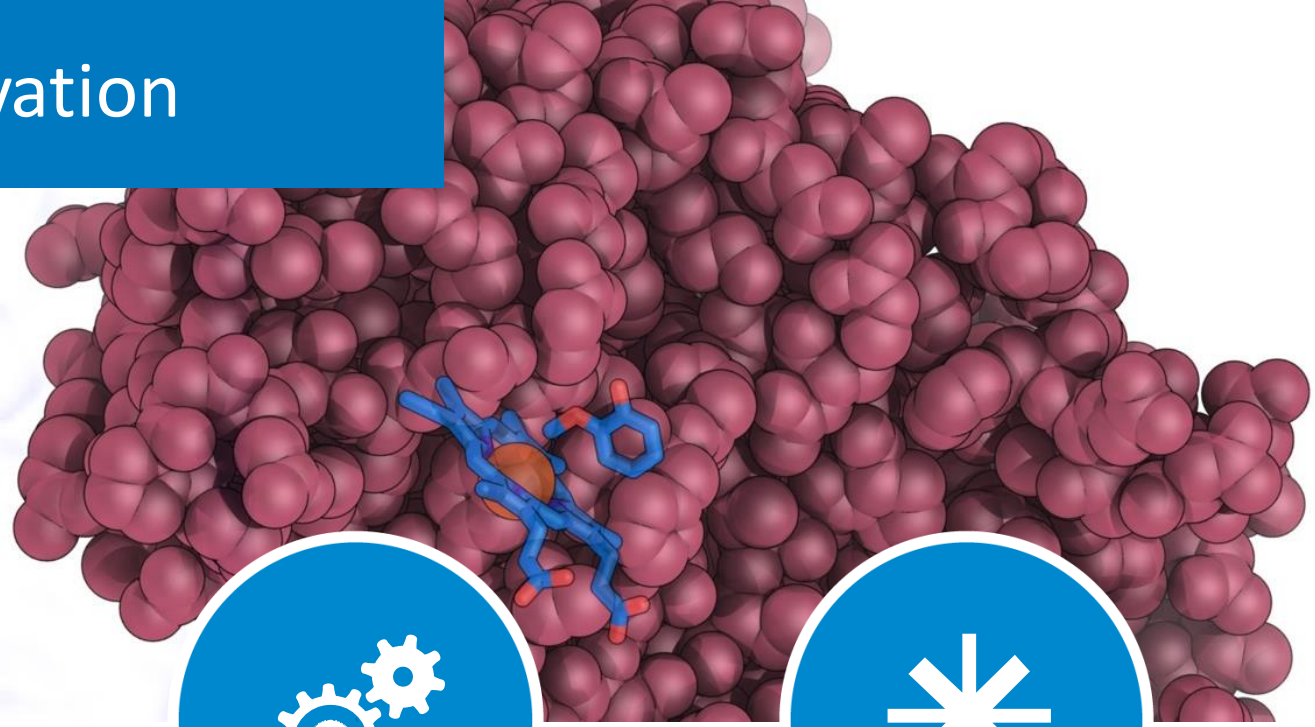
Partnerships
with industry, academia, and government

Campus
operates as a living laboratory

Images: NREL

NREL Science Drives Innovation





Renewable Power

Solar

Wind

Water

Geothermal

Sustainable Transportation

Bioenergy

Vehicle Technologies

Hydrogen

Energy Efficiency

Buildings

Advanced Manufacturing

Government Energy Management

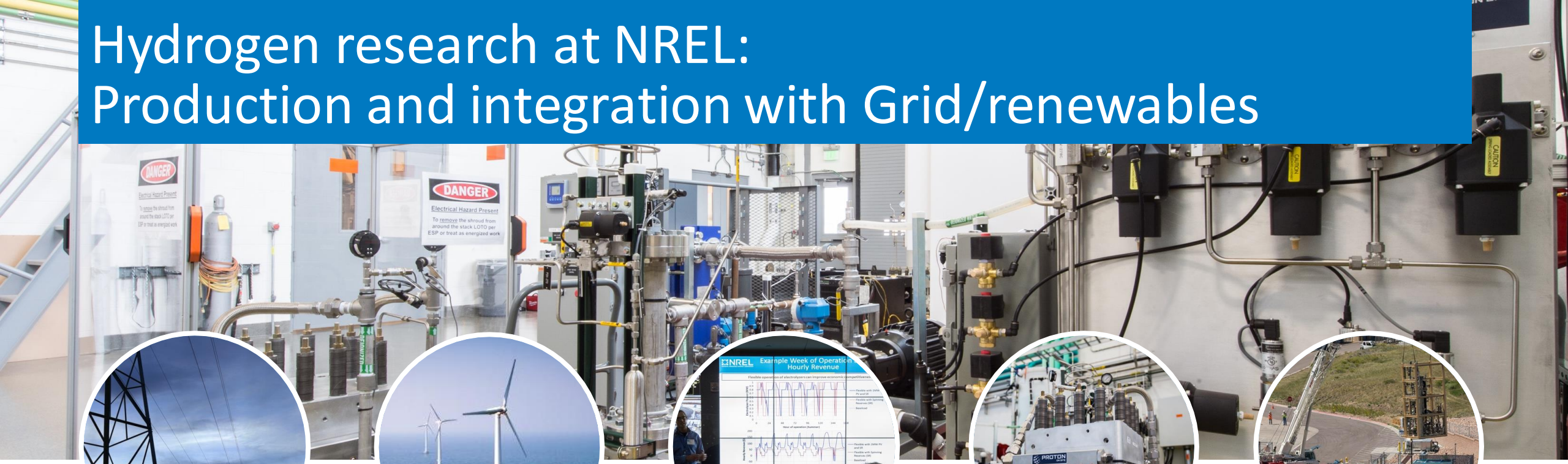
Energy Systems Integration

Grid Integration

Hybrid Systems

Security and Resilience

Hydrogen research at NREL: Production and integration with Grid/renewables



Grid Services

Electrolyzers as dispatchable loads integrated with power generation systems to mitigate disturbances

Renewables

Transient operations with AC and DC power operation and analysis: coupling to wind, OSW, MHK, PV, DCFC

Control

Energy systems control & optimization with Electrolysis, storage, end use as subsystems

Cell/Stack

Multiple stack test beds capable of variable sizes and operation conditions, including BOP

Molecules

Biological production of RNG through CO_2 and H_2 feedstocks

Images: NREL

Hydrogen research at NREL: Infrastructure

Fueling

HD fueling protocol support, 70MPa and -40°C fast fueling, HD station design and operations

Operations

Compression, storage management, precooling, safety controls, back-to-back and simultaneous fueling

Storage

Low, medium, high pressure ground storage, on-board vehicle storage (LD, HD), Type I – IV storage vessels

Components

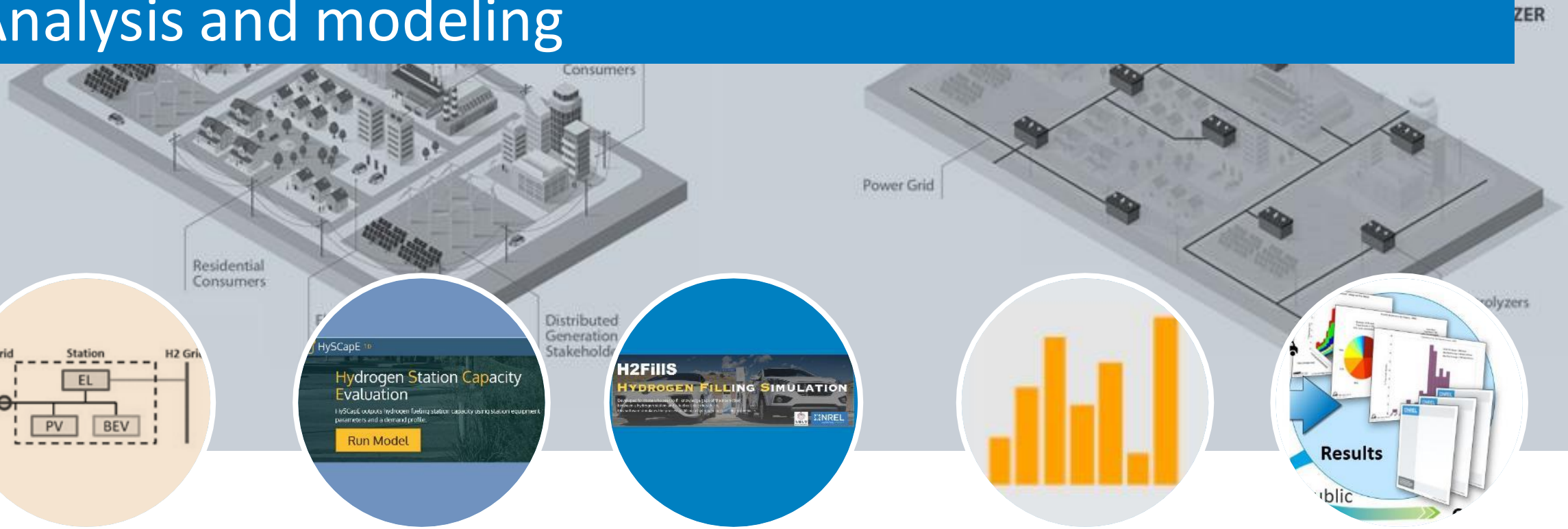
Reliability of early market components: valves, breakaways, nozzles, hoses

Hydrogen

On-site production for closed and open-loop H_2 research activities, tube trailer deliveries

Images: NREL

Hydrogen research at NREL: Analysis and modeling



Energy Systems

Bulk and distribution grid interactions with electrolyzers, front end controllers, station integration

Station Capacity

CEC hydrogen station capacity model, NREL internal model for station level simulations

Thermodynamics

H2FillS transient model for hydrogen vehicle filling simulation – station storage through vehicle

Systems Analysis

Process TEA, market status and adoption projections, resource assessment, cost-benefit analysis, financial analysis

Public Data

Composite data products from retail hydrogen stations: safety, reliability, performance, cost, etc.

Images: NREL

Hydrogen research at NREL: Safety

Integration

Integrate safety research into codes and standards

Components

Quantify component performance and failures from the field and in the lab

Sensors

Verify, validate, and develop prototype sensors with high accuracy and low cost

Monitoring

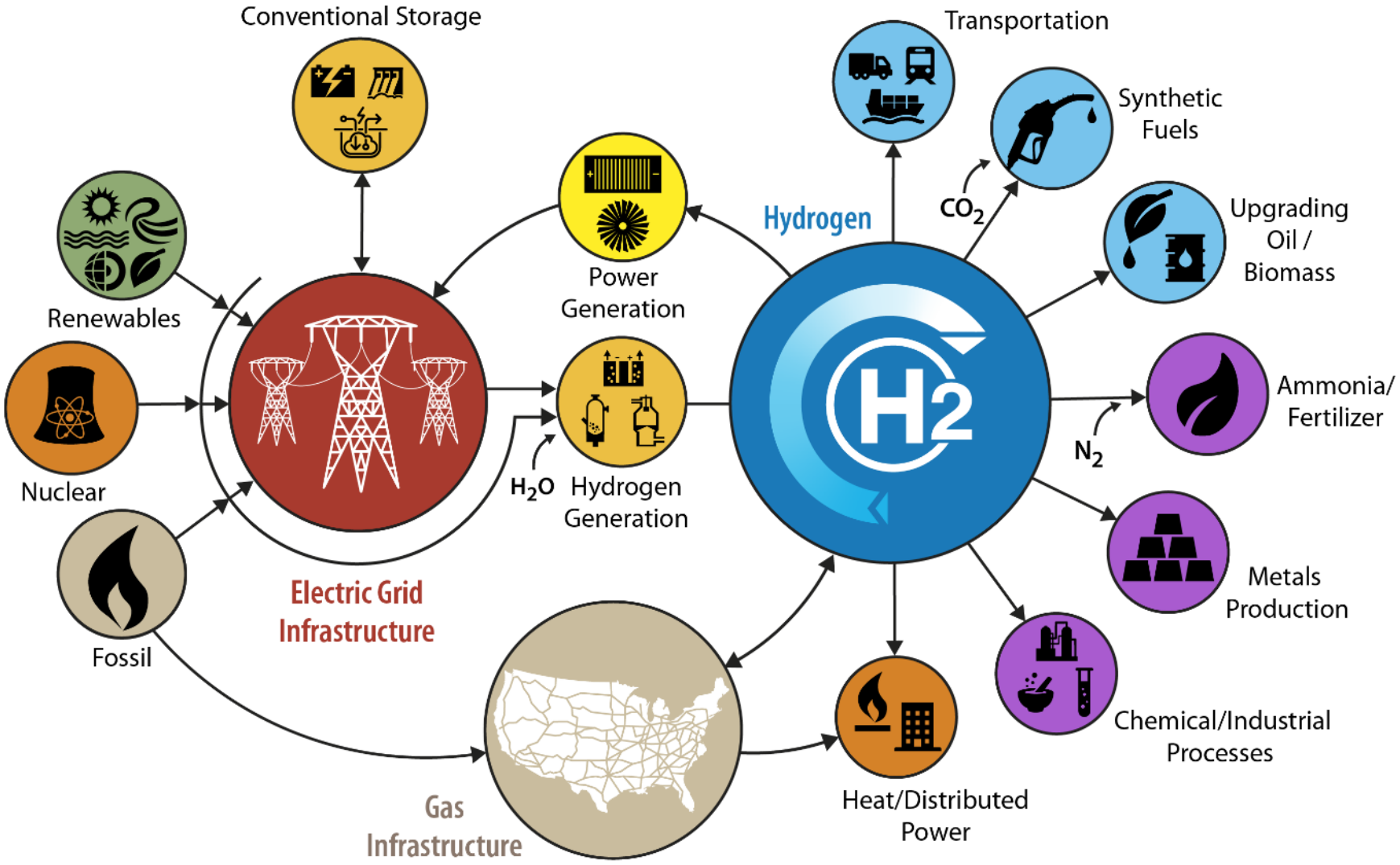
Development and deployment of sensors and safety systems for hydrogen purity, leak detection

Outreach

Connect users to safety requirements to advance safe deployment

Images: NREL

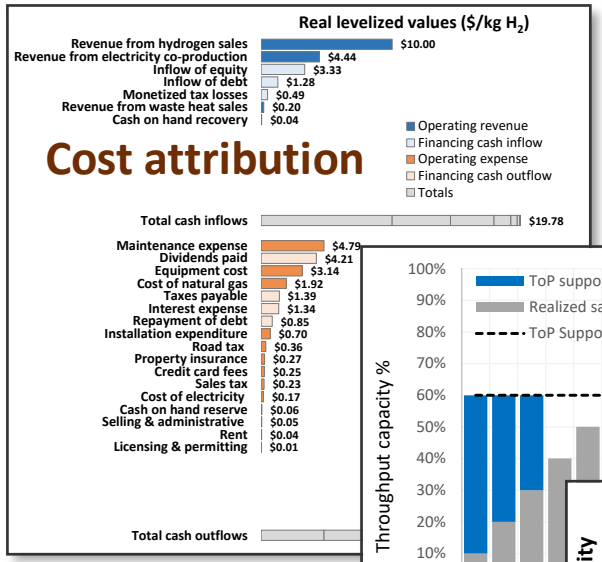
U.S. DOE and Hydrogen Fuel Cell Technology Office H2@Scale Vision imagines a robust hydrogen economy

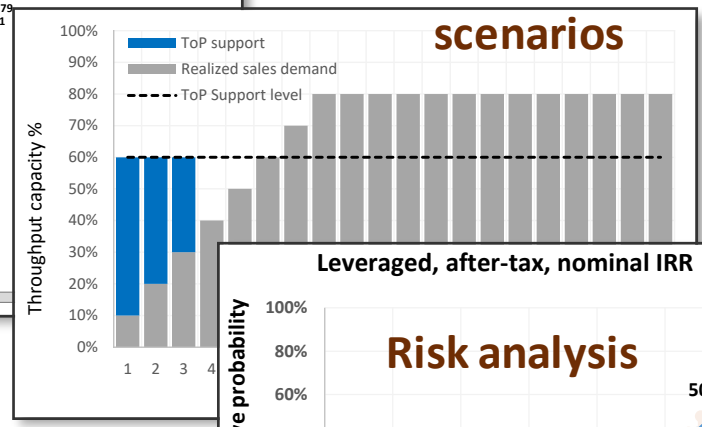


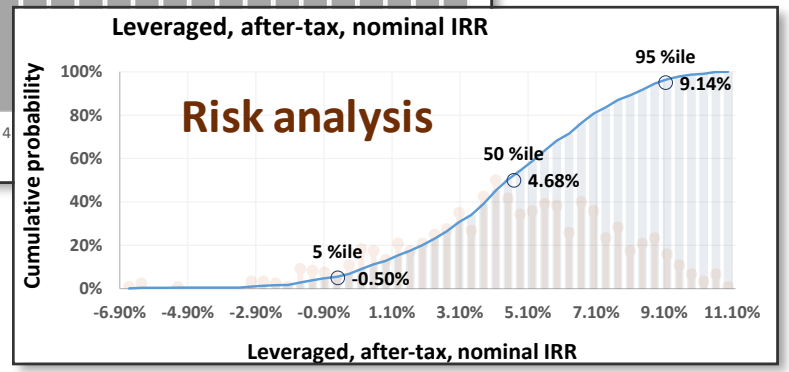
Project Financial Analysis with H2FAST

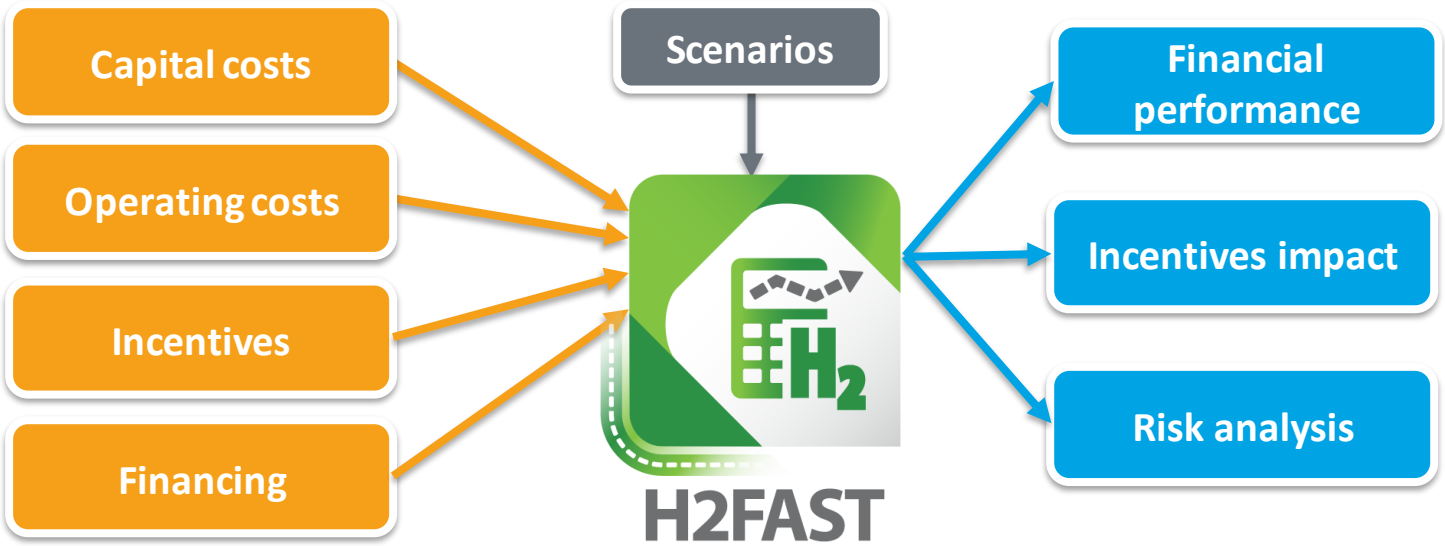
The ***Hydrogen Financial Analysis Scenario Tool*** **(H2FAST)**

- Generally accepted accounting principles (GAAP) analysis of individual hydrogen infrastructure projects (production, distribution, retail)
- Annual computation of income statements, cash flow statements, balance sheets.
- Cost attribution by category
- Incentive policy analysis
- Risk analysis





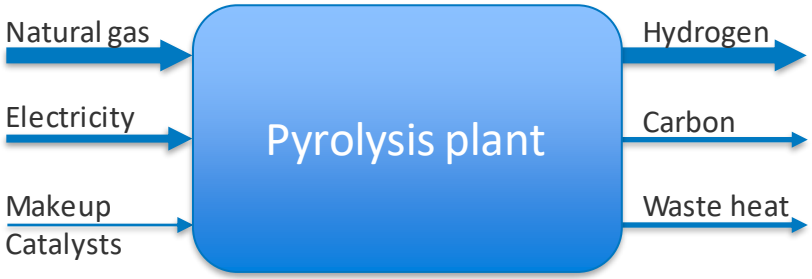




https://www.nrel.gov/hydrogen/h2fast.html

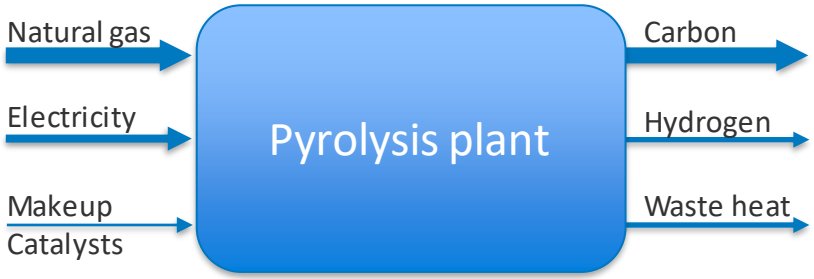
3 General Process Plants In Methane Pyrolysis Program

Hydrogen-centric processes



- Produces low-value carbon (e.g. graphitic carbon)
- Majority of revenue generated from sale of hydrogen

Carbon-centric processes



- Produces high value carbon (e.g. nano-tubes)
- Majority of revenues are from carbon products and hydrogen comprises small portion of overall revenue
- Can yield lowest cost hydrogen

Carbon upgrading processes

- Upgrades low value carbon products
- Does not produce hydrogen

Common Assumptions Among Project Analysis

Plant operating assumptions

- Start year 2020
- N'th plant capital cost estimate
- On-stream factor 95%
- Construction period 12 months
- Demand ramp-up 0 years
- Labor rate (fully loaded) $69/h

Financing assumptions

- After-tax nominal discount rate 8%
- Debt to equity ratio: 1.5
- Interest rate: 3.7%
- Income tax rate (federal & state) 25.7%
- Depreciation method 10-year MACRS
- General inflation 1.9%
- Working capital (liquidity): 1 month of operating expenses
- Reference dollars $2020 (cost reported for first year and subject to general inflation escalation in subsequent years)

Energy & feedstock cost assumptions

- Cost of industrial natural gas EIA 2021 Reference Case ($4.08/mmBTU in 2021)
- Cost of industrial electricity EIA 2021 Reference Case (7.3¢/kWh in 2021)
- Catalyst replacement cost escalation 1.9%
- Waste heat value = direct displacement rate of natural gas combustion
- Cost of CO_2 = $0/ton
- Waste disposal = $0/ton

Hydrogen-Centric Process
03 PARC, 2018 Open (Brad Rupp team)

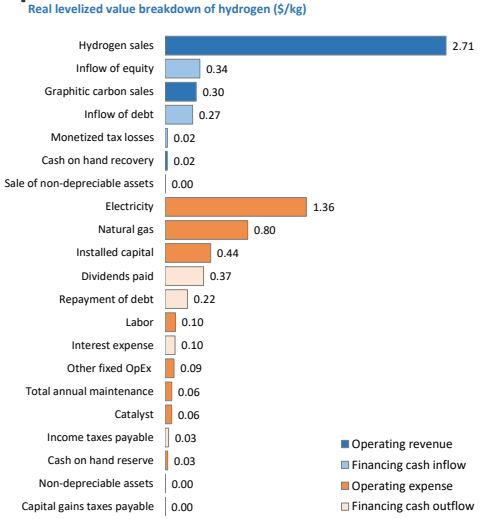
Overall Financial Performance Metrics	Most likely value
Leveraged, after-tax, nominal IRR	8.00%
Profitability index	1.20
Investor payback period	6 years
First year of positive EBITD	analysis year 2
After-tax, nominal NPV @ 8% discount	$0
Estimated break-even leveraged price (2020$/kg)	$2.71

Cumulative investor cash flow — Toggle chart labels

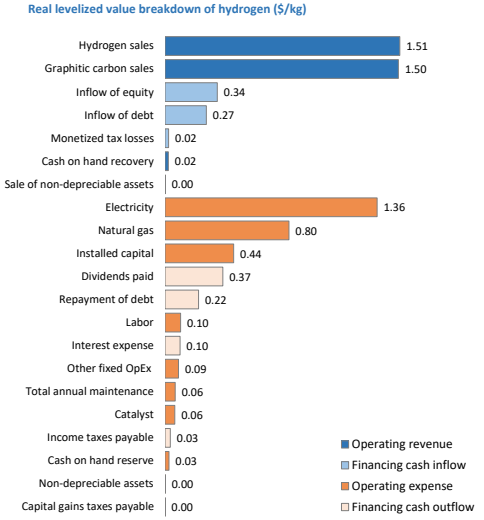
Installation(s) Information	Most likely value				Multiple scenarios?	Real levelized contribution
Capacity (kg/day)				10,000		
Commodity, retail units, capacity timeframe		hydrogen	kg	day		
Total of Itemized Equipment Cost	$	15,000,000	Dep. type	Dep. yrs		
Installed capital	$	15,000,000	MACRS	10 year		0.44
Non-depreciable assets	$			50,000		0.00
Sale of non-depreciable assets	$			60,355		0.00
Total annual maintenance				225,000		0.06
Maintenance escalation (% annually)				1.90%		
Feedstock Use						
Natural gas (mmBTU/kg)		0.200	natural gas	mmBTU		0.80
Electricity (kWh/kg)		20.000	electricity	kWh		1.36
Catalyst (kg/kg)		0.02100	catalyst	kg		0.06
CO2 emissions (m.tonne/kg)		0.0002	CO2 emissions	m.tonne		0.00
Co-product Specifications						
Graphitic carbon (kg/kg)		3.000	graphitic carbon	kg		0.30
Process heat (mmBTU/kg)			process heat	mmBTU		0.00
Sales Specification						
Price of hydrogen at project onset ($/kg)				$2.71		2.71
Price escalation rate (% annually)				1.90%		
Project initiation (year of financing)				2020		
Project operational life (years)				10		
Installation time (months)				12		
Demand ramp-up (years)				0.0		
Long-term nominal utilization (%)				95%		
Feedstock Cost						
Cost of natural gas ($/mmBTU)	$			7.00		0.80
Escalation rate of cost (% annually)				1.90%		
Cost of electricity ($/kWh)	$			0.120		1.36
Escalation rate of cost (% annually)				1.90%		
Cost of catalyst ($/kg)	$			3.000		0.06
Escalation rate of cost (% annually)				1.90%		
Cost of CO2 emissions ($/m.tonne)	$			-		0.00
Escalation rate of cost (% annually)				1.90%		
Co-Product Value						
Value of graphitic carbon ($/kg)	$			0.10		0.30
Escalation rate of cost (% annually)				1.90%		
Value of process heat ($/mmBTU)	$			-		0.00
Escalation rate of cost (% annually)				1.90%		
Other Operating Expenses						
Staffing labor hours (h/year)				5,000		0.10
Labor rate ($/h)	$			69		
Labor escalation rate (% annually)				1.9%		
Other fixed OpEx ($/year)	$	300,000		Other fixed OpEx		0.09
Other fixed OpEx escalation (% annually)				1.90%		
Financing Information						
Total tax rate (state, federal, local)				25.74%		0.03
Capital gains tax				15.00%		0.00
Is installation cost depreciable?				Yes		
Are operating incentives taxable?				No		
Is capital incentive depreciable?				Yes		
Sell residual depreciable capital at end of analysis?				Yes		
Are tax losses monetized (tax equity application)				Yes		0.02
Allowable tax loss carry-forward				7 year		
General inflation rate				1.90%		
Depreciation method				MACRS		
Depreciation period				10 year		
Leveraged after-tax nominal discount rate				8.0%		
Debt/equity financing				1.50		
Debt type				Revolving debt		
If loan, period of loan (years)				15		
Debt interest rate (compounded monthly)				3.70%		0.10
Cash on hand (% of monthly expenses)				100%		0.00

Overall Financial Performance Metrics Scenario History		
Leveraged, after-tax, nominal IRR	8%	8%
Profitability index	1.20	1.20
Investor payback period	6 years	6 years
First year of positive EBITD	analysis year 2	analysis year 2
After-tax, nominal NPV @ 8% discount	$ -	$ -
Estimated break-even leveraged price (2020$/kg)	$2.71	$1.51
Scenario being analyzed (yellow background)	1	2
Installation name	Graphitic carbon = $100/m.tonne	Graphitic carbon = $500/m.tonne
Co-Product Value		
Value of graphitic carbon ($/kg)	$ 0.100	$ 0.500

Graphitic carbon = $100/m.ton



Graphitic carbon = $500/m.ton



Nano-tube Centric Process
Stanford TINA 2019 (Matteo Cargnello team)

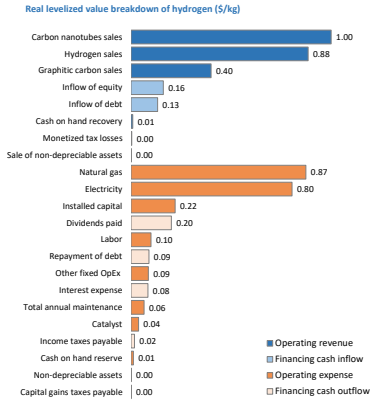
Overall Financial Performance Metrics	Most likely value
Leveraged, after-tax, nominal IRR	8.00%
Profitability index	1.45
Investor payback period	9 years
First year of positive EBITD	analysis year 2
After-tax, nominal NPV @ 8% discount	$0
Estimated break-even leveraged price (2020$/kg)	$0.88

Cumulative investor cash flow | Toggle chart labels

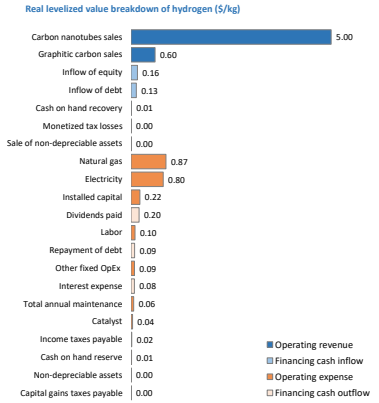
Installation(s) Information	Most likely value				Multiple scenarios?	Real levelized contribution ($/kg)
Capacity (kg/day)				10,000		
Commodity, retail units, capacity timeframe		hydrogen	kg	day		
Total of Itemized Equipment Cost	$	15,000,000	Dep. type	Dep. yrs		
Installed capital	$	15,000,000	MACRS	20 year		0.22
Non-depreciable assets	$			50,000		0.00
Sale of non-depreciable assets	$			72,854		0.00
Total annual maintenance				225,000		0.06
Maintenance escalation (% annually)				1.90%		
Feedstock Use						
Natural gas (mmBTU/kg)		0.210	natural gas	mmBTU		0.87
Electricity (kWh/kg)		12.000	electricity	kWh		0.80
Catalyst (kg/kg)		0.00300	catalyst	kg		0.04
CO2 emissions (m.tonne/kg)		0.1750	CO2 emissions	m.tonne		0.00
Co-product Specifications						
Graphitic carbon (kg/kg)		2.000	graphitic carbon	kg		0.40
Process heat (mmBTU/kg)			process heat	mmBTU		0.00
Carbon nanotubes (kg/kg)		1.000	carbon nanotubes	kg		1.00
Sales Specification						
Price of hydrogen at project onset ($/kg)				$0.88		0.88
Price escalation rate (% annually)				1.90%		
Project initiation (year of financing)				2020		
Project operational life (years)				20		
Installation time (months)				12		
Demand ramp-up (years)				0.0		
Long-term nominal utilization (%)				95%		
Feedstock Cost						
Cost of natural gas ($/mmBTU)	$			7.00		0.87
Escalation rate of cost (% annually)				1.90%		
Cost of electricity ($/kWh)	$			0.120		0.80
Escalation rate of cost (% annually)				1.90%		
Cost of catalyst ($/kg)	$			12.500		0.04
Escalation rate of cost (% annually)				1.90%		
Cost of CO2 emissions ($/m.tonne)	$			-		0.00
Escalation rate of cost (% annually)				1.90%		
Co-Product Value						
Value of graphitic carbon ($/kg)	$			0.20		0.40
Escalation rate of cost (% annually)				1.90%		
Value of process heat ($/mmBTU)	$			-		0.00
Escalation rate of cost (% annually)				1.90%		
Value of carbon nanotubes ($/kg)	$			1.00		1.00
Escalation rate of cost (% annually)				1.90%		
Other Operating Expenses						
Staffing labor hours (h/year)				5,000		0.10
Labor rate ($/h)	$			69		
Labor escalation rate (% annually)				1.9%		
Other fixed OpEx ($/year)	$		300,000	Other fixed OpEx		0.09
Other fixed OpEx escalation (% annually)				1.90%		
Financing Information						
Total tax rate (state, federal, local)				25.74%		0.02
Capital gains tax				15.00%		0.00
Is installation cost depreciable?				Yes		
Are operating incentives taxable?				No		
Is capital incentive depreciable?				Yes		
Sell residual depreciable capital at end of analysis?				Yes		
Are tax losses monetized (tax equity application)				Yes		0.00
Allowable tax loss carry-forward				7 years		
General inflation rate				1.90%		
Depreciation method				MACRS		
Depreciation period				20 year		
Leveraged after-tax nominal discount rate				8.0%		
Debt/equity financing				1.50		
Debt type				Revolving debt		
If loan, period of loan (years)				15		
Debt interest rate (compounded monthly)				3.70%		0.08
Cash on hand (% of monthly expenses)				100%		0.00

Overall Financial Performance Metrics Scenario History			
Leveraged, after-tax, nominal IRR	8%	8%	8%
Profitability index	1.45	1.45	1.45
Investor payback period	9 years	9 years	9 years
First year of positive EBITD	analysis year 2	analysis year 2	analysis year 2
After-tax, nominal NPV @ 8% discount	$ -	$ -	$ -
Estimated break-even leveraged price (2020$/kg)	$0.88	($3.32)	($8.52)
Scenario being analyzed (yellow background)	1	2	3
Installation name	High cost estimate	Mid cost estimate	Low cost estimate
Capacity (kg/day)			
Installed capital			
Non-depreciable assets			
Sale of non-depreciable assets			
Total annual maintenance			
Maintenance escalation (% annually)			
Feedstock Use			
Natural gas (mmBTU/kg)			
Electricity (kWh/kg)			
Catalyst (kg/kg)			
CO2 emissions (m.tonne/kg)			
Co-product Specifications			
Graphitic carbon (kg/kg)			
Process heat (mmBTU/kg)			
Carbon nanotubes (kg/kg)			
Sales Specification			
Price of hydrogen at project onset ($/kg)			
Price escalation rate (% annually)			
Project initiation (year of financing)			
Project operational life (years)			
Installation time (months)			
Demand ramp-up (years)			
Long-term nominal utilization (%)			
Feedstock Cost			
Cost of natural gas ($/mmBTU)			
Escalation rate of cost (% annually)			
Cost of electricity ($/kWh)			
Escalation rate of cost (% annually)			
Cost of catalyst ($/kg)			
Escalation rate of cost (% annually)			
Cost of CO2 emissions ($/m.tonne)			
Escalation rate of cost (% annually)			
Co-Product Value			
Value of graphitic carbon ($/kg)	$ 0.200	$ 0.300	$ 0.400
Escalation rate of cost (% annually)			
Value of process heat ($/mmBTU)			
Escalation rate of cost (% annually)			
Value of carbon nanotubes ($/kg)	$ 1.000	$ 5.000	$ 10.000
Escalation rate of cost (% annually)			
Other Operating Expenses			
Staffing labor hours (h/year)			
Labor rate ($/h)			
Labor escalation rate (% annually)			
Other fixed OpEx ($/year)			
Other fixed OpEx escalation (% annually)			
Financing Information			
Total tax rate (state, federal, local)			
Capital gains tax			
Is installation cost depreciable?			
Are operating incentives taxable?			
Is capital incentive depreciable?			
Sell residual depreciable capital at end of analysis?			
Are tax losses monetized (tax equity application)			
Allowable tax loss carry-forward			
General inflation rate			
Depreciation method			
Depreciation period			
Leveraged after-tax nominal discount rate			
Debt/equity financing			
Debt type			
If loan, period of loan (years)			
Debt interest rate (compounded monthly)			
Cash on hand (% of monthly expenses)			

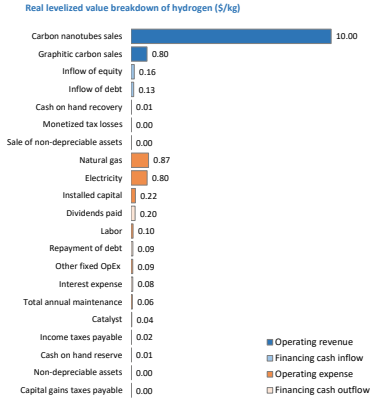
Low C value case: ($200/tonne graphitic, $1000/tonne nanotubes)
Low C- value-> Highest H_2 revenue needed $0.88/kg



Mid C value case: ($300/tonne graphitic, $5,000/tonne nanotubes)
Low C- value-> H_2 revenue is not needed to achieve financial performance (negative $3.3/kg H_2)



Hgih C value case: ($400/tonne graphitic, $10,000/tonne nanotubes)
Low C- value-> H_2 revenue is not needed to achieve financial performance (negative $8.5/kg H_2)



Carbon upgrading process
05 JHU TINA 2019 (Chao Wang team)

Overall Financial Performance Metrics	Most likely value
Leveraged, after-tax, nominal IRR	8.00%
Profitability index	3.17
Investor payback period	14 years
First year of positive EBITD	analysis year 4
After-tax, nominal NPV @ 8% discount	$0
Estimated break-even leveraged price (2020$/kg)	$7.01
Cumulative investor cash flow	Toggle chart labels

Installation(s) Information	Most likely value			Min/max
Capacity (kg/day)			10,000	
Commodity, retail units, capacity timeframe	carbon fiber	kg	day	
Total of Itemized Equipment Cost	$ 50,000,000	Dep. type	Dep. yrs	
Installed capital	$ 50,000,000	MACRS	20 year	
Non-depreciable assets	$		625,000	
Sale of non-depreciable assets	$		1,326,928	
Total annual maintenance			2,500,000	
Maintenance escalation (% annually)			1.90%	

Feedstock Use			
Natural gas (mmBTU/kg)	-	natural gas	mmBTU
Electricity (kWh/kg)	19.900	electricity	kWh
Catalyst (kg/kg)		catalyst	kg
CO2 emissions (m.tonne/kg)	0.00007	CO2 emissions	m.tonne
Hazardous waste generation (units of feedstock 5/kg)	0.042	Hazardous waste gene	units of feedstock 5
Precursors (kg/kg)	2.100	precursors	kg
Feedstock 7 (units of feedstock 7/kg)		feedstock 7	units of feedstock 7
Feedstock 8 (units of feedstock 8/kg)		feedstock 8	units of feedstock 8
Feedstock 9 (units of feedstock 9/kg)		feedstock 9	units of feedstock 9

Co-product Specifications			
Graphitic carbon (kg/kg)		graphitic carbon	kg
Process heat (mmBTU/kg)	0.0600	process heat	mmBTU

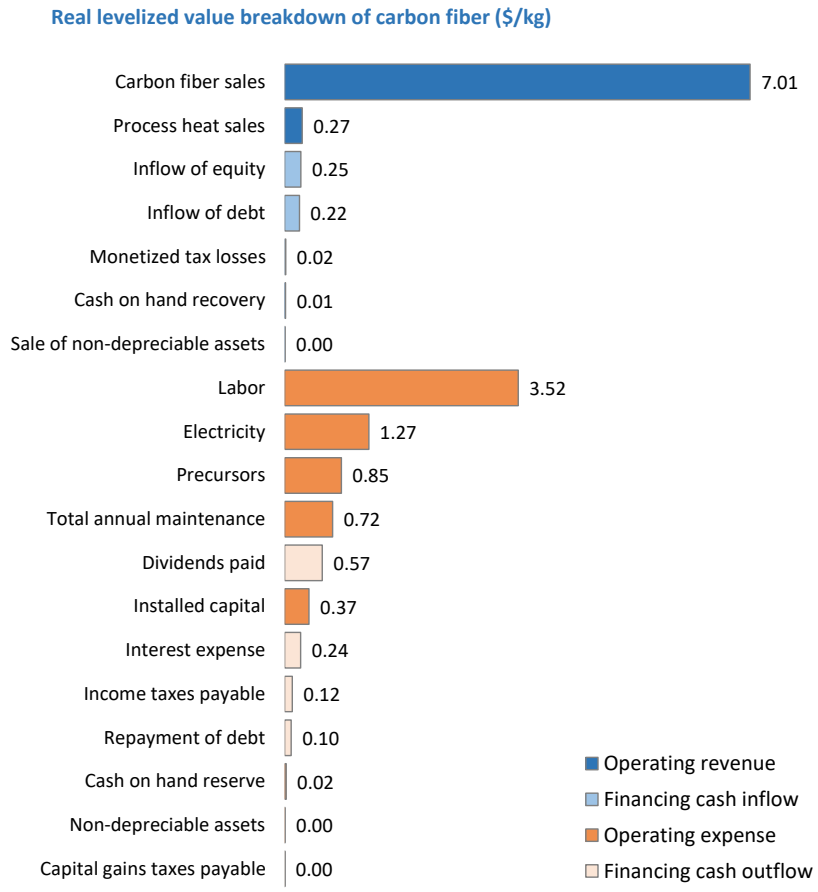
Sales Specification	
Price of carbon fiber at project onset ($/kg)	$7.01
Price escalation rate (% annually)	1.90%
Project initiation (year of financing)	2020
Project operational life (years)	40
Installation time (months)	36
Demand ramp-up (years)	0.0
Long-term nominal utilization (%)	95%

Feedstock Cost		
Cost of catalyst ($/kg)	$	16.500
Escalation rate of cost (% annually)		1.90%
Cost of CO2 emissions ($/m.tonne)	$	-
Escalation rate of cost (% annually)		1.90%
Cost of Hazardous waste generation ($/units of feedstock	$	-
Escalation rate of cost (% annually)		1.90%
Cost of precursors ($/kg)	$	0.407
Escalation rate of cost (% annually)		1.90%

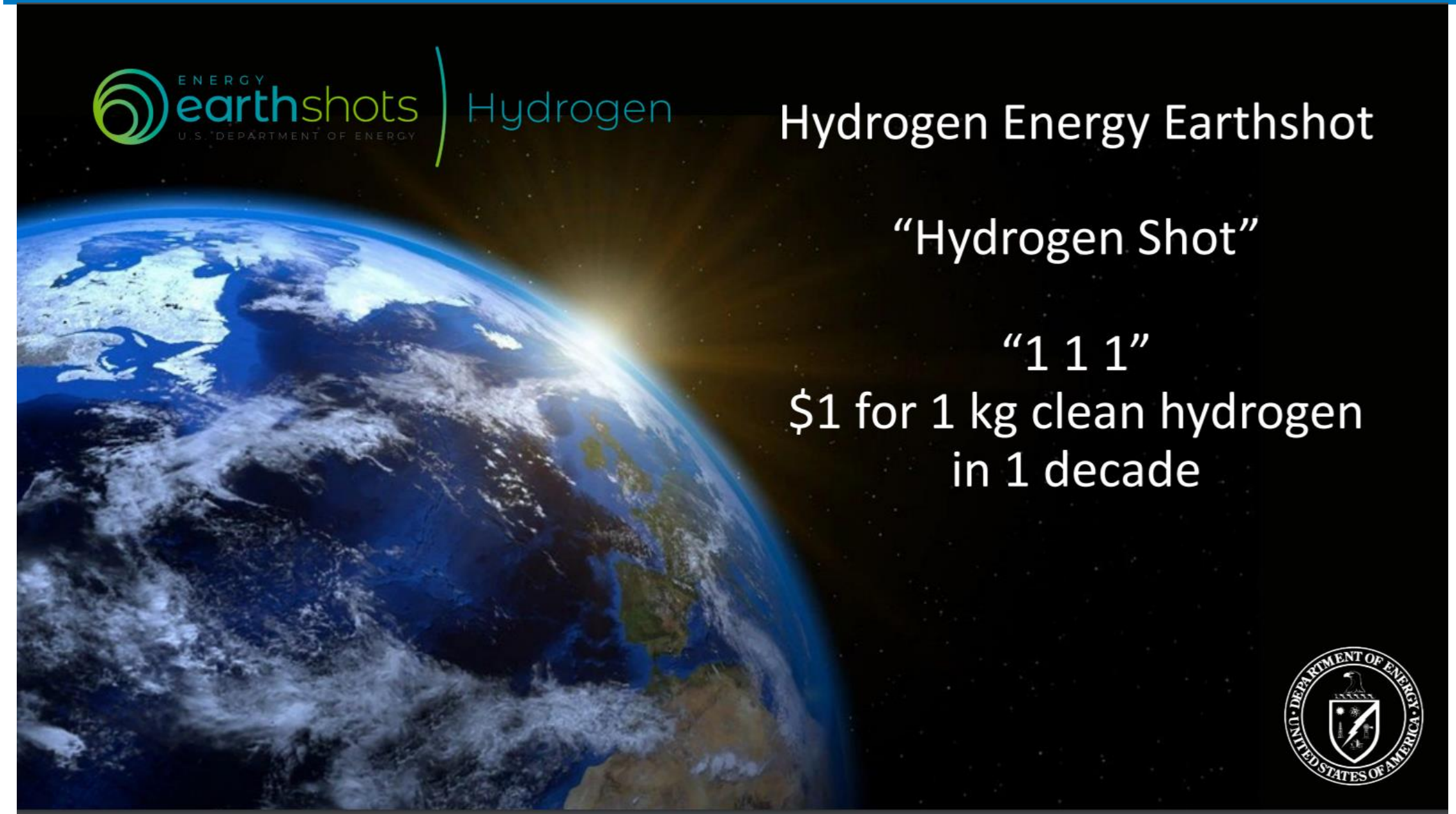
Co-Product Value		
Value of graphitic carbon ($/kg)	$	0.25
Escalation rate of cost (% annually)		1.90%
Value of process heat ($/mmBTU)	$	-
Escalation rate of cost (% annually)		1.90%

Other Operating Expenses		
Staffing labor hours (h/year)		176,000
Labor rate ($/h)	$	69
Labor escalation rate (% annually)		1.9%

Financing Information	
Total tax rate (state, federal, local)	25.74%
Capital gains tax	15.00%
Is installation cost depreciable?	Yes
Are operating incentives taxable?	No
Is capital incentive depreciable?	Yes
Sell residual depreciable capital at end of analysis?	Yes
Are tax losses monetized (tax equity application)	Yes
Allowable tax loss carry-forward	7 year
General inflation rate	1.90%
Depreciation method	MACRS
Depreciation period	20 year
Leveraged after-tax nominal discount rate	8.0%
Debt/equity financing	1.50
Debt type	Revolving debt
If loan, period of loan (years)	15
Debt interest rate (compounded monthly)	3.70%
Cash on hand (% of monthly expenses)	100%



Methane Pyrolysis Has Potential of Satisfying the Hydrogen Energy Earthshot

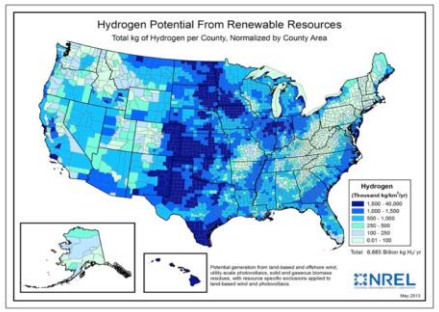


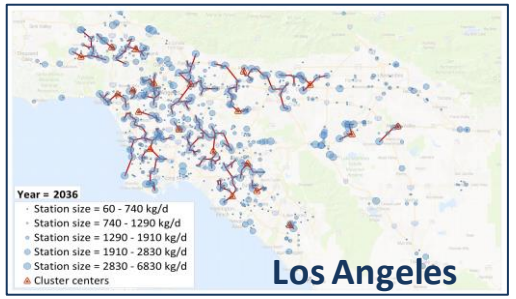
Pyrolysis May be Prudent Addition to Pathways of Supply Chain Modeling In SERA

The SERA model simulates least-cost hydrogen infrastructure supply systems for urban FCEV markets

SERA

Energy Resources	Hydrogen Production	Storage & Delivery	Retail Station Networks





- Energy prices (natural gas, electricity, etc.)
- Renewables (biomass, solar, wind)
- Terrain, rights of way, etc.

- Central and onsite production facilities
- Capacity sized to meet forecasted demand
- Economies of scale balanced with delivery costs

- Truck delivery, rail, and pipeline.
- Cost is sensitive to volume, distance
- Seasonal and weekly storage
- Networked supply to multiple cities

- Coverage stations for FCEV introductions
- Station sizes increase with market growth
- Liquid and pipeline delivery networks compete for large stations

Thank you.

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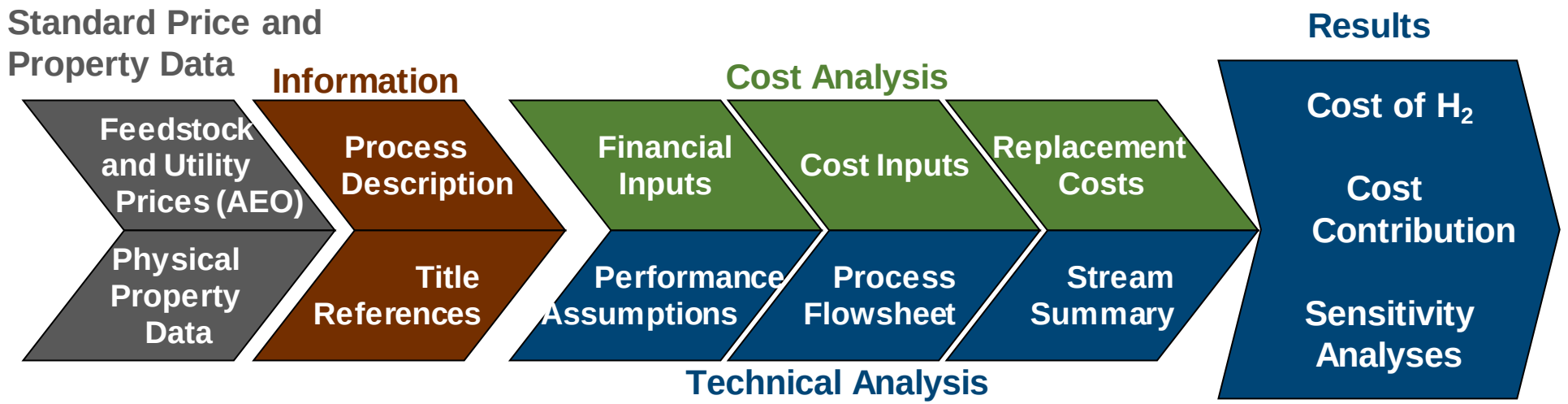
www.nrel.gov

H2FAST model, case studies, and documentation:
https://www.nrel.gov/hydrogen/h2fast.html

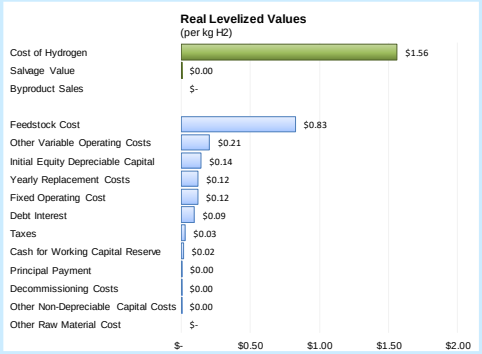
NREL H2 Production Economic Tools: H2A

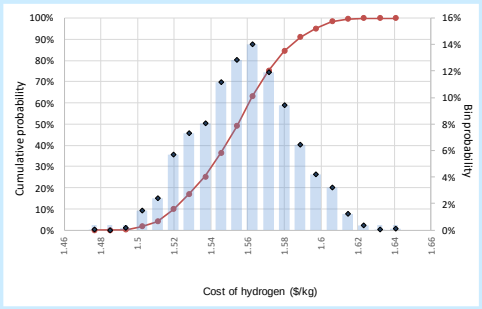


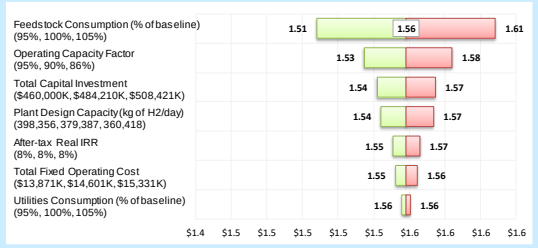
Spreadsheet Examples

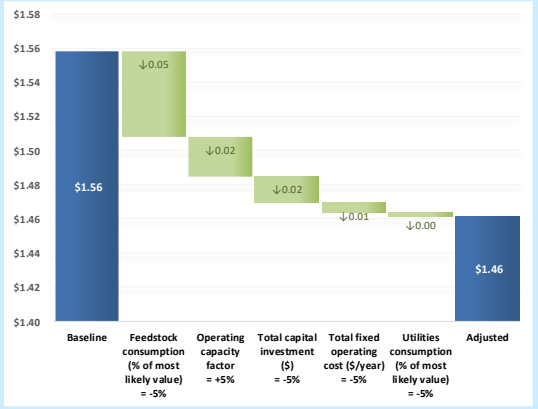
AEO_2017_Reference_Case
Year
Feedstock Type
Residential Natural Gas
Commercial Natural Gas
Industrial Natural Gas
Electric Utility Natural Gas
Woody Biomass
Electric Utility Steam Coal
Commercial Electricity
Industrial Electricity
Residential Electricity

Technical Operating Parameters and Specifications	
Operating Capacity Factor (%)	90.0%
Plant Design Capacity (kg of H2/day)	379,387
Plant Output (kg/day)	341,448
Plant Output (kg/year)	124,628,630
Financial Input Values	
Reference year	2016
Assumed start-up year	2015
Basis year	2005
Length of Construction Period (years)	3
% of Capital Spent in 1st Year of Construction	8%
% of Capital Spent in 2nd Year of Construction	60%
% of Capital Spent in 3rd Year of Construction	32%
% of Capital Spent in 4th Year of Construction	
Start-up Time (years)	1
Plant life (years)	40
Analysis period (years)	40
Depreciation Schedule Length (years)	20
Depreciation Type	MACRS
% Equity Financing	40%
Interest rate on debt, if applicable (%)	3.70%
Debt period (years)	Constant debt
% of Fixed Operating Costs During Start-up (%)	75%
% of Revenues During Start-up (%)	50%
% of Variable Operating Costs During Start-up (%)	75%
Decommissioning costs (% of depreciable capital investment)	10%
Salvage value (% of total capital investment)	10%
Inflation rate (%)	1.9%
After-tax Real IRR (%)	8.0%
State Taxes (%)	6.0%
Federal Taxes (%)	21.0%
Total Tax Rate (%)	25.74%
WORKING CAPITAL (% of yearly change in operating costs)	15%









https://www.nrel.gov/hydrogen/h2a-production-models.html